

TWO-SCALE COST EFFICIENCY OPTIMIZATION OF 5G WIRELESS BACKHAUL NETWORKS

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Abstract

To cater for the demands of future fifth generation (5G) ultra-dense small cell networks, the wireless backhaul network is an attractive solution for the urban deployment of 5G wireless networks. Optimization of 5G wireless backhaul networks is a key issue. In this paper we propose a two-scale optimization solution to maximize the cost efficiency of 5G wireless backhaul networks. Specifically, the number and positions of gateways are optimized in the long time scale of 5G wireless backhaul networks. The wireless backhaul routings are optimized in the short time scale of 5G wireless backhaul networks. Numerical results show the cost efficiency of proposed optimization algorithm is better than the cost efficiency of conventional and most widely used shortest path (SP) algorithm in 5G wireless backhaul networks.

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I. INTRODUCTION

With the exponentially increasing demand for wireless data traffic in recent years, traditional macro cellular networks can not handle gigabit-level data traffic in an economical and ecological way [1]. The fifth generation (5G) small cell network, adopting massive multiple input multiple output (MIMO) and millimeter wave transmission technologies, is emerging as a promising solution [2]. In order to reduce the cell coverage sharply to achieve a high spatial spectrum efficiency, a large number of small cells have to be deployed to realize the seamless coverage in urban regions and form 5G ultra-dense cellular networks [3]. However, it is uneconomical and cost-prohibitive for every small cell to be connected with the fiber to the cell (FTTC). As a consequence, wireless backhaul networks form an indispensable solution of 5G ultra-dense small cell networks [4]. Moreover, 5G small cell networks equipped with massive MIMO antennas and millimeter wave transmission technology provide enough redundant resource, e.g. antennas and bandwidth for wireless backhaul transmission. Therefore, it is an important and challenging problem to optimize the cost efficiency of 5G wireless backhaul networks.

The feasibility of massive MIMO and millimeter wave transmission technologies for 5G wireless backhaul networks were discussed in [5]–[9]. The differences compared with the conventional massive MIMO technology working at 3~6 GHz for radio access networks and the benefits of the wireless backhaul for 5G ultra-dense networks with the technology of massive MIMO were discussed in [5]. In [6], Zhang *et al.* provided a state-of-the-art survey on large-scale (LS)-MIMO studies and then proposed a joint group power allocation and pre-beamforming scheme to substantially improve the performance of LS-MIMO-based wireless backhaul in heterogeneous wireless networks. Based on the beam alignment technique using adaptive subspace sampling and hierarchical beam codebooks, the millimeter wave beamforming transmission technology was developed for both wireless backhaul and access in small cell networks [7]. Dat *et al.* proposed and experimentally demonstrated a seamlessly converged radio-over-fiber (RoF) and millimeter-wave system at 90 GHz for high-speed wireless signal transmission [8]. The above results confirmed the potential to use millimeter wave transmission technologies in wireless backhaul networks. An in-band solution, i.e., multiplexing backhaul and access on the same frequency band was proposed to meet the backhaul and inter base station (BS) coordination challenges [9]. Simulation results showed that an in-band wireless backhaul for data backhauling and inter-BS

coordination is feasible without significantly hurting the cellular access capacities.

Millimeter wave transmission technologies employing 60 GHz and 70~80 GHz are usually used for line-of-sight (LOS) links in short ranges [10], [11]. Hence, multi-hop implementation is needed for long ranges in wireless backhaul networks adopting millimeter wave transmission technologies. Connectivity is an important issue to make all the nodes in multi-hop networks interconnected and reachable [12]. Moreover, methods corresponding to graph theory are proved effective with the analysis of wireless multi-hop networks [13], [14]. Aimed at the joint maximization of energy and spectrum efficiency in wireless backhaul networks, a user association scheme was developed for heterogeneous wireless network where small cells forward their traffic through backhaul links to neighboring small cells until it eventually reaches the core network [15]. Considering the backhaul channel conditions and the quality of service requirements, an optimal joint routing and backhaul link scheduling scheme was proposed for a dense small cell network using 60 GHz multi-hop backhaul links [16]. Based on the evolutionary game theory, an adaptive routing strategy was developed for IEEE 802.16 multi-hop wireless backhaul networks [17]. Utilizing dual connectivity establishment methods, a self-organized multi-hop backhaul establishment procedure was developed to support autonomous bidirectional beam alignments for heterogeneous wireless backhaul networks [18]. Extended from a graph theoretic clique idea, a new adaptive backhaul architecture was proposed in [19] which allows changes to the overall backhaul topology and each individual backhaul link can vary its frequency to meet traffic demand. However, the deployment of multiple gateways in wireless backhaul networks has not been considered in [16]–[19]. In our previous work [20], energy efficiency of small cell backhaul networks was studied. Furthermore, a basic wireless backhaul network architecture with multiple gateways configurations was proposed in [21]. How to optimize the number and positions of multiple gateways in 5G wireless backhaul networks is still an open issue. Besides, the joint optimization of the multiple gateways deployment and wireless backhaul links has not been investigated in 5G wireless backhaul networks. Moreover, the total cost efficiency optimization for 5G wireless backhaul networks is surprisingly rare in the open literature.

Motivated by the above observations, in this paper we propose a two-scale cost efficiency optimization solution for 5G wireless backhaul networks. The contributions and novelties of this paper are summarized as follows.

- 1) We propose a cost efficiency model for 5G wireless backhaul networks considering multiple

gateways deployment and wireless channel conditions.

- 2) To optimize the cost efficiency of 5G wireless backhaul networks, a two-scale joint optimization solution has been proposed. In the long time scale, the number and positions of gateways are optimized by the long time optimization (LTO) algorithm. In the short time scale, the wireless backhaul routings are optimized by the maximum capacity spanning tree (MCST) algorithm.
- 3) Numerical results show that there exists an optimal number of gateways for maximizing the cost efficiency of 5G wireless backhaul networks and the proposed algorithms are better than the conventional and widely used shortest path (SP) algorithm.

The rest of this paper is organized as follows. Section II describes the system model of 5G wireless backhaul networks. The cost efficiency of 5G wireless backhaul networks is formulated in Section III. Furthermore, a two-scale joint optimization solution is proposed for the cost efficiency optimization of 5G wireless backhaul networks in Section IV. Simulation analysis is presented in Section V. Finally, Section VI concludes this paper.

II. SYSTEM MODEL

The millimeter wave transmission technology is assumed to be adopted for 5G wireless backhaul networks. Considering the large path loss fading in millimeter wave propagations, the maximum distance of every hop in 5G wireless backhaul networks is limited to D_0 meters. The basic transmission models studied in this paper are described in Fig. 1.

A. Connection Cluster Model

The coverage of a macro cell BS (MBS) is assumed to be a circle with a radius R and a total of n small cell BSs (SBSs) are deployed in the coverage of the MBS. The MBS takes charge of the control plane and SBSs take charge of traffic transmission in this system. In this paper, the 5G wireless backhaul network comprises of SBSs in the coverage of a MBS. Every SBS can connect with other SBSs within the distance D_0 . The set \mathcal{V} includes n SBSs and is divided into connection clusters, where the total number of connection clusters is denoted by B . There is no link between two connection clusters. The generating algorithm of connection cluster is illustrated as follows:

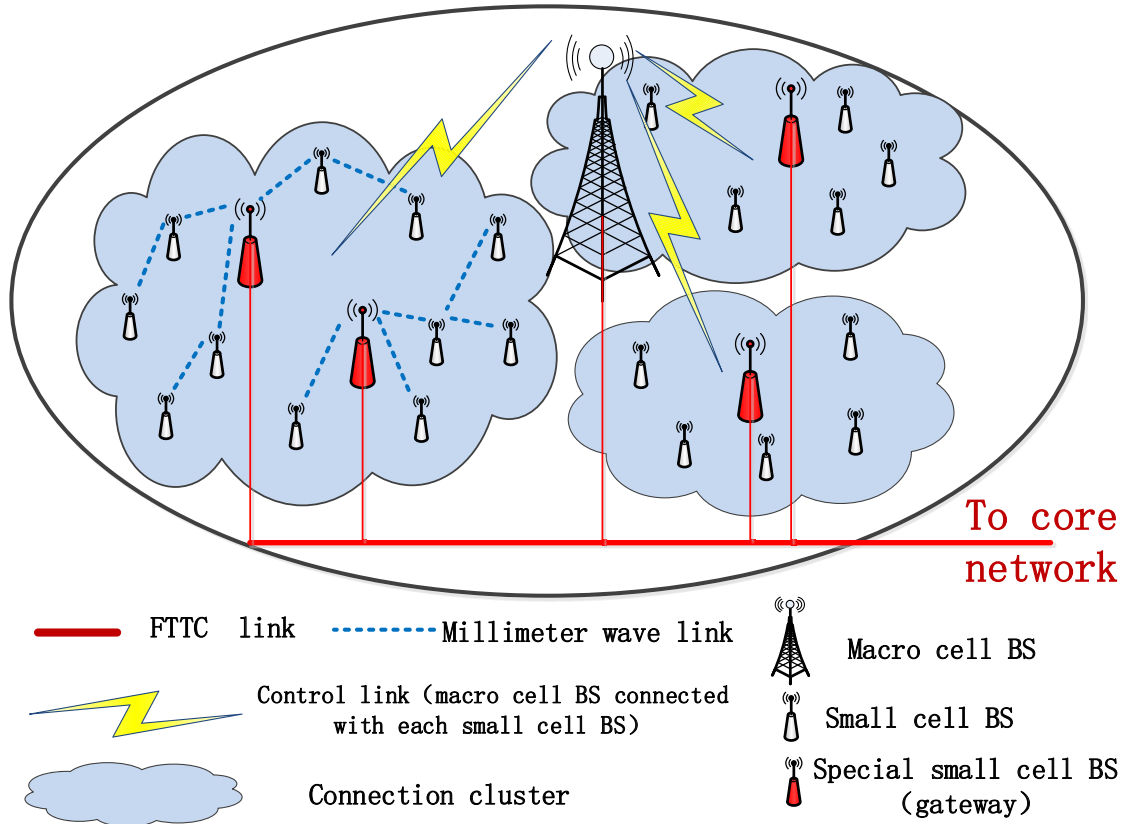


Fig. 1. System model.

Using the generating algorithm of connection clusters, n SBSs are divided into B connection clusters. To guarantee the forwarding of wireless backhaul traffic to the core network, every connection cluster must deploy more than one gateway to connect with the core network. Therefore, the number of gateways must be larger than or equal to the number of connection clusters, i.e., $M \geq B$.

B. Network Capacity Model

Without loss of generality, assume that there are M SBSs out of the total n SBSs configured as gateways. It follows that the number of the rest non-gateway SBSs is equal to $N = n - M$. In this study we focus on the wireless backhaul traffic, i.e., the traffic transmitted from N SBSs to the M gateways. Let $N_{i,j,T}^x$ be the number of bits transmitted by the SBS SBS_i and which

Algorithm 1 The generating algorithm of connection cluster.

Input: The location of all the small cell BSs $\{(x_p, y_p), SBS_p \in \mathcal{V}\}$, n

- 1) **Initialization:** The connection cluster $\Psi = \phi$, the number of the cluster is $B = 0$, the temporary cluster is $\Theta = \phi$, $v = 0$, $t = 0$.
- 2) **while** $v < n$ **do**

$$\Theta = \phi; v \leftarrow v + 1; t \leftarrow 0$$

if $B > 0$ **then**

for $i = 1 : B$ **do**

for $j = 1 : |\Phi_i|$ **do**

The distance between small cell BS SBS_v and SBS_j is D_{vj} :

$$D_{vj} \leftarrow \sqrt{(x_v - x_j)^2 + (y_v - y_j)^2};$$

if $D_{vj} \leq D_0$ **then**

$$\Theta = \Theta + \{SBS_p, SBS_p \in \Phi_i\}; t \leftarrow t + 1; break;$$

end if

end for

end for

end if

$$B \leftarrow B + 1;$$

if $t == 0$ **then**

$$\Phi_B = \{SBS_v\};$$

else

$$\Phi_B = \{SBS_q, SBS_q \in \Theta\} + \{SBS_v\};$$

Delete the clusters which have been put into Φ_B and label the elements in Ψ in the original order.

end if

end while

Output: Connection clusters $\Psi = \{\Phi_i\}, i = 1, 2, \dots, B$.

reached, i.e., successfully received by, the respective gateway GW_j during a time interval $[0, T]$, with T being an arbitrarily large number. The superscript $\chi \in \Omega$ represents the spatial and temporal scheduling algorithm used in the wireless backhaul network and Ω denotes the set of all scheduling algorithms. If the same bit is transmitted from a SBS to multiple gateways, e.g., in the case of multicast, it is counted as one bit in the calculation of $N_{i,j,T}^\chi$.

It is assumed that the wireless backhaul network is stable $\forall \chi \in \Omega$. A wireless backhaul network is called stable if and only if the long-term incoming traffic rate into the wireless backhaul network equals the long-term outgoing traffic rate. It is further assumed that there is no traffic loss caused by queue overflow. The transport capacity using the spatial and temporal scheduling algorithm χ in a connection cluster with M gateways and N SBSs, denoted by $C^\chi(M, N)$, is defined as:

$$C^\chi(M, N) \triangleq \lim_{T \rightarrow \infty} \frac{\sum_{i=1}^N \sum_{j=1}^M N_{i,j,T}^\chi}{T}. \quad (1)$$

and the network capacity with M gateways and N SBSs in the wireless backhaul network is defined as

$$C(M, N) \triangleq \max_{\chi \in \Omega} C^\chi(M, N). \quad (2)$$

Considering M gateways deployed in the wireless backhaul network, the average throughput of each gateway is derived by

$$\bar{C}(M, N) \triangleq \frac{C(M, N)}{M}. \quad (3)$$

C. Link Traffic Model

Assume that there exist K types of wireless traffic in the wireless backhaul network. The set including all types of wireless traffic is denoted as $\mathcal{K} := \{1, \dots, \tau, \dots, K\}$ and the set of all links is denoted as \mathcal{L} for the wireless backhaul network. Without loss of generality, the τ -th type of wireless traffic is assumed to be transmitted by the link $l \in \mathcal{L}(\tau)$ and the average transmission rate of the τ -th wireless traffic is assumed as a^τ . The average transmission rate of the SBS SBS_i with the τ -th wireless traffic is assumed as a_i^τ . If the SBS SBS_i is the traffic source then $a_i^\tau = a^\tau$. If the SBS SBS_i is the traffic destination then $a_i^\tau = -a^\tau$. If the SBS SBS_i is the relaying SBS then $a_i^\tau = 0$. The formulation of a_i^τ is expressed by

$$a_i^\tau = \begin{cases} a^\tau, & \text{if } SBS_i \text{ is the source of } \tau\text{-th traffic} \\ -a^\tau, & \text{if } SBS_i \text{ is the destination of } \tau\text{-th traffic} \\ 0, & \text{otherwise} \end{cases}. \quad (4)$$

The input and output transmission rates of the SBS SBS_i with the τ -th traffic type are denoted as r_{ji}^τ and r_{iq}^τ , respectively. When the SBS SBS_i is configured as the source or relay SBS, the

input traffic of the $\tau - th$ traffic is equal to the output traffic of the $\tau - th$ traffic at the SBS SBS_i [24], which is expressed by

$$a_i^\tau + \sum_{SBS_j \in \mathcal{V}_i^{in}} r_{ji}^\tau = \sum_{SBS_q \in \mathcal{V}_i^{out}} r_{iq}^\tau, \forall SBS_i \in \mathcal{V}, SBS_i \neq d_\tau, \forall \tau \in \mathcal{K}, \quad (5)$$

where d_τ is the destination for the $\tau - th$ traffic, the set of input links and the set of output links at the SBS SBS_i is denoted by \mathcal{L}_i^{in} and \mathcal{L}_i^{out} , the set of input SBSs and the set of output SBSs with respect to the SBS SBS_i are denoted by $\mathcal{V}_i^{in} = \{SBS_j : (SBS_i, SBS_j) \in \mathcal{L}_i^{in}\}$ and $\mathcal{V}_i^{out} = \{SBS_j : (SBS_i, SBS_j) \in \mathcal{L}_i^{out}\}$, respectively.

The capacity of the link l is assumed to be c_l and the transmission rate of the $\tau - th$ traffic at the link l is denoted as r_l^τ . Different types of wireless traffic are assumed to be multiplexed over the same link l . Hence, the relationship of the capacity of the link l and the sum transmission rate of different types of wireless traffic over the link l is expressed by

$$\sum_{\tau \in \mathcal{K}} r_l^\tau \leq c_l, l \in \mathcal{L}. \quad (6)$$

D. Wireless Transmission Model

Every SBS is equipped with N_T and N_R antennas for wireless transmission and reception, respectively. The millimeter wave frequency is adopted for wireless transmission in the wireless backhaul network. The large scale fading over the millimeter wave link is expressed by

$$\Psi = \beta + 10\gamma \log_{10} \Delta + S, \quad (7a)$$

with

$$\beta = 20 \log_{10} \left(\frac{4\pi}{\lambda} \right), \quad (7b)$$

where λ is the wave length, γ is the path loss coefficient, Δ is the distance between the transmitter and receiver, S is the shadowing fading effect which is governed by the Gaussian distribution with zero mean and variance ξ^2 , i.e., $S \sim N(0, \xi^2)$.

Assume that the millimeter wave transmission of SBSs is limited to line-of-sight (LOS)

transmissions. The wireless channel matrix of SBSs is expressed by [25]

$$\begin{aligned}\mathbf{H} &= \sqrt{\frac{N_T N_R}{\Psi \cdot \eta}} \cdot \sum_{u=1}^{\eta} \alpha_u \mathbf{a}_r(\theta_u^r) \mathbf{a}_t(\theta_u^t)^* \\ &= \sqrt{\frac{N_T N_R}{\Psi \cdot \eta}} \cdot \mathbf{A}_R \mathbf{D} \mathbf{A}_T^*\end{aligned}\quad (8a)$$

with

$$\mathbf{A}_R = [\mathbf{a}_r(\theta_1^r) | \mathbf{a}_r(\theta_2^r) | \dots | \mathbf{a}_r(\theta_\eta^r)] , \quad (8b)$$

$$\mathbf{A}_T = [\mathbf{a}_t(\theta_1^t) | \mathbf{a}_t(\theta_2^t) | \dots | \mathbf{a}_t(\theta_\eta^t)] , \quad (8c)$$

$$\mathbf{D} = \text{diag} \{ \alpha_1, \alpha_2, \dots, \alpha_\eta \} , \quad (8d)$$

where η is the number of paths between the transmitter and the receiver, α_u is the small scale fading over the u -th path and is a complex normally distributed random variable with zero mean and unit variance, θ_u^r is the virtual angles of arrival (AOA) and θ_u^t is the virtual angles of departure (AOD) for the u -th path, $\mathbf{a}_r(\theta_u^r)$ and $\mathbf{a}_t(\theta_u^t)$ are the receiving and transmitting antenna array response vectors, respectively. θ_u^r and θ_u^t are assumed to be uniformly distributed in the range of $[0, 2\pi]$ and then $\mathbf{a}_r(\theta_u^r)$ and $\mathbf{a}_t(\theta_u^t)$ are extended by [5]

$$\mathbf{a}_r(\theta_u^r) = \frac{1}{\sqrt{N_R}} [1, e^{j2\pi d \sin(\theta_u^r)/\lambda}, \dots, e^{j2\pi(N_R-1)d \sin(\theta_u^r)/\lambda}]^T , \quad (9)$$

$$\mathbf{a}_t(\theta_u^t) = \frac{1}{\sqrt{N_T}} [1, e^{j2\pi d \sin(\theta_u^t)/\lambda}, \dots, e^{j2\pi(N_T-1)d \sin(\theta_u^t)/\lambda}]^T , \quad (10)$$

where d is the distance among antennas.

The millimeter wave MIMO transmission system in the 5G wireless backhaul network is illustrated in Fig. 2. For the multi-point to single-point transmission link l in 5G wireless backhaul network, the transmitters include Q SBS equipped with N_T antennas and the receiver is a SBS equipped with N_R antennas. Moreover, the number of antennas at receiver is assumed to be larger than Q times of the antenna number at transmitters, i.e., $N_R > Q N_T$. The numbers of radio frequency (RF) chains at the transmitter and receiver are N_{RF}^T and N_{RF}^R , respectively. For the SBS SBS_i , the signal vector \mathbf{s}_i consisted by $N_{S,T}^i$ data streams is processed by the digital precoding $\mathbf{P}_D \in N_{RF}^T \times N_{S,T}^i$ and then transmitted into N_{RF}^T RF chains. Furthermore, the signal

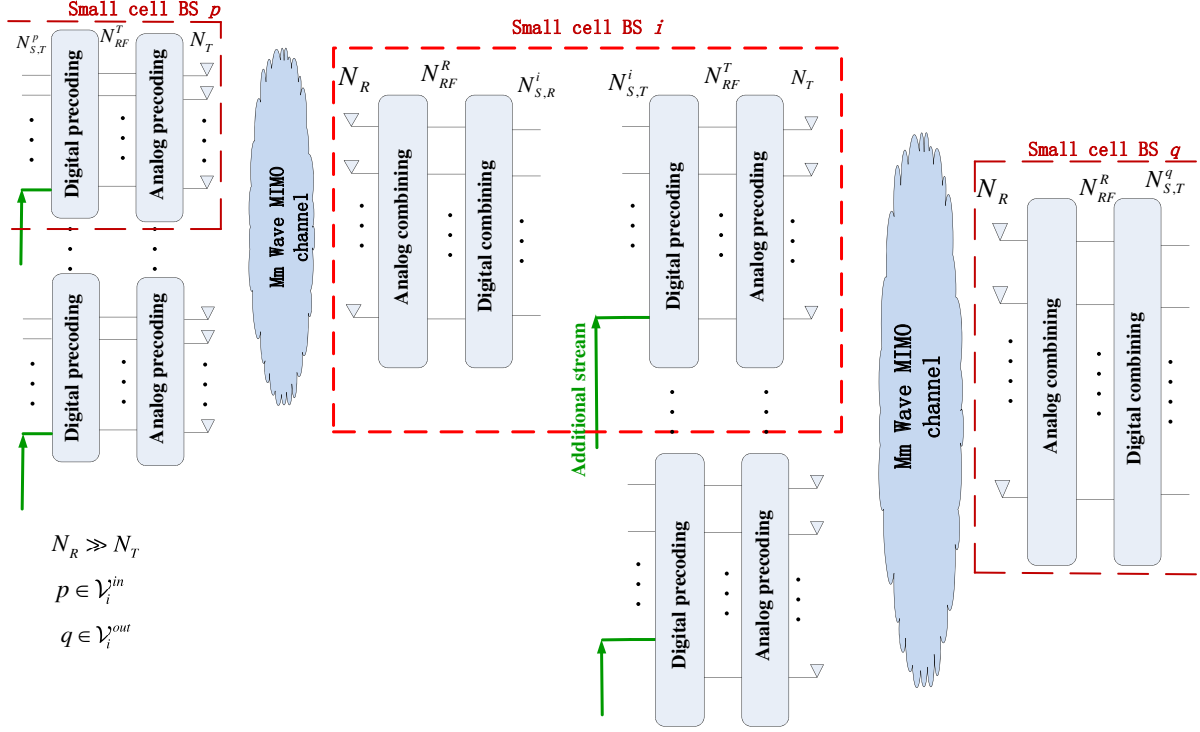


Fig. 2. The millimeter wave MIMO transmission system.

passed through RF chains is transmitted into N_T transmission antennas by the analog precoding $\mathbf{P}_A \in \mathbb{C}^{N_T \times N_{RF}^T}$. Hence, the transmitted signal at the SBS SBS_i is expressed by $\mathbf{x}_i = \mathbf{P}_A \mathbf{P}_D \mathbf{s}_i$. When \mathbf{x}_i is received by the SBS SBS_q with N_R receive antennas, the received signal is expressed by

$$\mathbf{y}_q = \sqrt{P_i} \mathbf{H}_l \mathbf{P}_A \mathbf{P}_D \mathbf{s}_i + \mathbf{n}, \quad (11)$$

where P_i is the transmission power at the SBS SBS_i , \mathbf{n} is the additive white Gaussian noise (AWGN) with variance σ^2 . Furthermore, the signal \mathbf{y}_q is processed by the analog decoding $\mathbf{F}_A \in \mathbb{C}^{N_R \times N_{RF}^R}$ and the digital decoding $\mathbf{F}_D \in \mathbb{C}^{N_{RF}^R \times N_{S,T}^i}$. In the end, the received data streams are expressed by

$$\tilde{\mathbf{y}}_q = \sqrt{P_i} \mathbf{F}_D^* \mathbf{F}_A^* \mathbf{H}_l \mathbf{P}_A \mathbf{P}_D \mathbf{s}_i + \mathbf{F}_D^* \mathbf{F}_A^* \mathbf{n}. \quad (12)$$

III. COST EFFICIENCY FORMULATION

A. Connection Probability and Non-isolation Probability

In this paper the distribution of SBSs is assumed to be governed by a Poisson point process with density μ . The probability that there exist n SBSs in a special coverage with area \mathcal{A} is expressed by

$$P_r[n \text{ SBSs in } \mathcal{A}] = e^{-\mu\mathcal{A}} \frac{(\mu\mathcal{A})^n}{n!}. \quad (13)$$

Based on the system model in Fig. 1, in this paper all SBSs are covered by a MBS. In this case, a SBS is isolated when the SBS can not build a backhaul link with other SBSs in the given coverage of MBS. The coverage area of a MBS is divided into a circular region \mathcal{A}_1 with the radius $R - D_0$ and the circular ring region \mathcal{A}_2 with the radius D_0 , which is shown in Fig. 3(a). When a SBS is located in the circular region \mathcal{A}_1 , the coverage area of the SBS in the coverage area of the MBS is $\mathcal{A}(r) = \pi D_0^2$, which is depicted in Fig. 3(b). When a SBS is located in the circular ring region \mathcal{A}_2 , the coverage area of the SBS in the coverage area of the MBS is $\mathcal{A}'(r) = D_0^2 \cdot \arccos \frac{r^2 + D_0^2 - R^2}{2D_0r} + R^2 \cdot \arccos \frac{r^2 - D_0^2 + R^2}{2Rr} - \frac{1}{2}\sqrt{\xi}$, $R - D_0 \leq r \leq R$, which is presented in Fig. 3(c). Based on the illustration in Fig. 3, the probability that a SBS is isolated is expressed by

$$\begin{aligned} P(\text{iso SBS}) &= P(\text{iso SBS} | \text{SBS is in } \mathcal{A}_1) P(\text{SBS is in } \mathcal{A}_1) + P(\text{iso SBS} | \text{SBS is in } \mathcal{A}_2) P(\text{SBS is in } \mathcal{A}_2) \\ &= e^{-\mu\mathcal{A}(r)} \cdot \frac{\pi(R - D_0)^2}{\pi R^2} + \int_{R-D_0}^R e^{-\mu\mathcal{A}'(r)} \cdot \frac{2\pi r \cdot dr}{\pi R^2} \\ &= e^{-\mu\pi D_0^2} \cdot \left(1 - \frac{D_0}{R}\right)^2 + \int_{R-D_0}^R e^{-\mu\left(D_0^2 \arccos \frac{r^2 + D_0^2 - R^2}{2D_0r} + R^2 \arccos \frac{r^2 - D_0^2 + R^2}{2Rr} - \frac{1}{2}\sqrt{\xi}\right)} \cdot \frac{2r \cdot dr}{R^2} \end{aligned} \quad (14a)$$

With

$$\xi = (r + D_0 + R)(-r + D_0 + R)(r - D_0 + R)(r + D_0 - R), \quad (14b)$$

Furthermore, the probability that there is no isolated SBS in the coverage of the MBS is

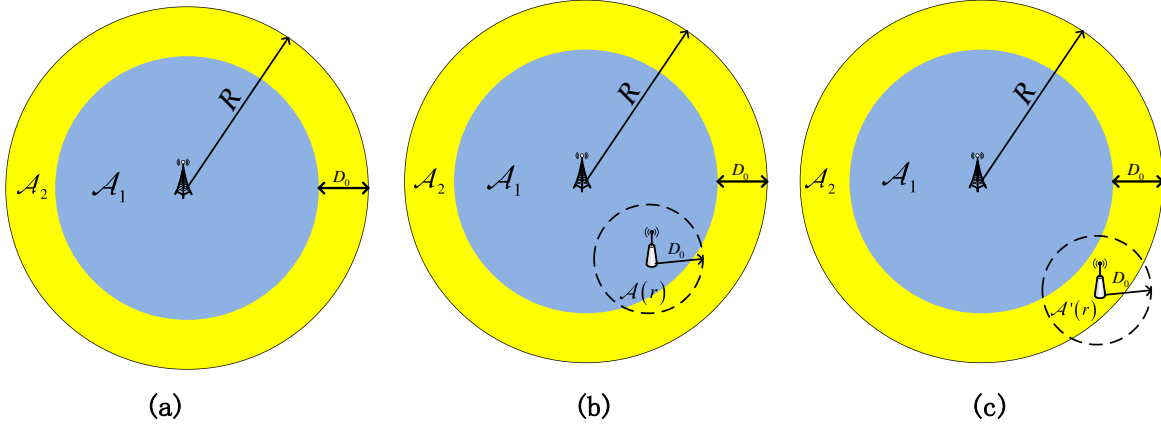


Fig. 3. Coverage regions of the MBS and SBSs

expressed by

$$\begin{aligned} P(\text{non-iso SBS}) &= (1 - P(\text{iso SBS}))^{E(N(\mathcal{A}))} \\ &= (1 - P(\text{iso SBS}))^{\mu\pi R^2}, \end{aligned} \quad (15)$$

Where $E(\cdot)$ is the expectation operation, $N(\mathcal{A})$ is the number of SBSs in the special coverage of the MBS with the area \mathcal{A} .

The probability that all SBSs are connected in the coverage of the MBS is denoted by $P(\text{con})$. The event that there is no isolated SBS in the coverage of the MBS is the necessary condition for the event that all SBSs are connected in the coverage of the MBS. Hence, we can get a constrain as $P(\text{con}) \leq P(\text{non-iso SBS})$. To validate this constrain, $P(\text{con})$ and $P(\text{non-iso SBS})$ are simulated by Monte Carlo (MC) and numerical (Num) methods in Fig. 4, where the radius of coverage of the MBS is $R = 500$ meters and the radius of SBS is $D_0 = 200$ meters.

From Fig. 4, the numerical and the MC results of $P(\text{non-iso SBS})$ are coincident. This result implies that the expression of $P(\text{non-iso SBS})$ is reasonable. When the value of SBSs density μ is larger than or equal to 125, $P(\text{non-iso SBS})$ is approximated with $P(\text{con})$. Therefore, we derive the following Theorem 1.

Theorem 1: When the coverage radius of the MBS R and the coverage radius of SBSs D_0 are given, if the density of SBSs is large enough, the probability that there is no isolated SBSs in the coverage of the MBS and the probability that all SBSs are connected in the coverage of the MBS have the following relationships: $P(\text{no iso SBS}) - P(\text{con}) \rightarrow 0$, $P(\text{no iso SBS}) \rightarrow 1$ and

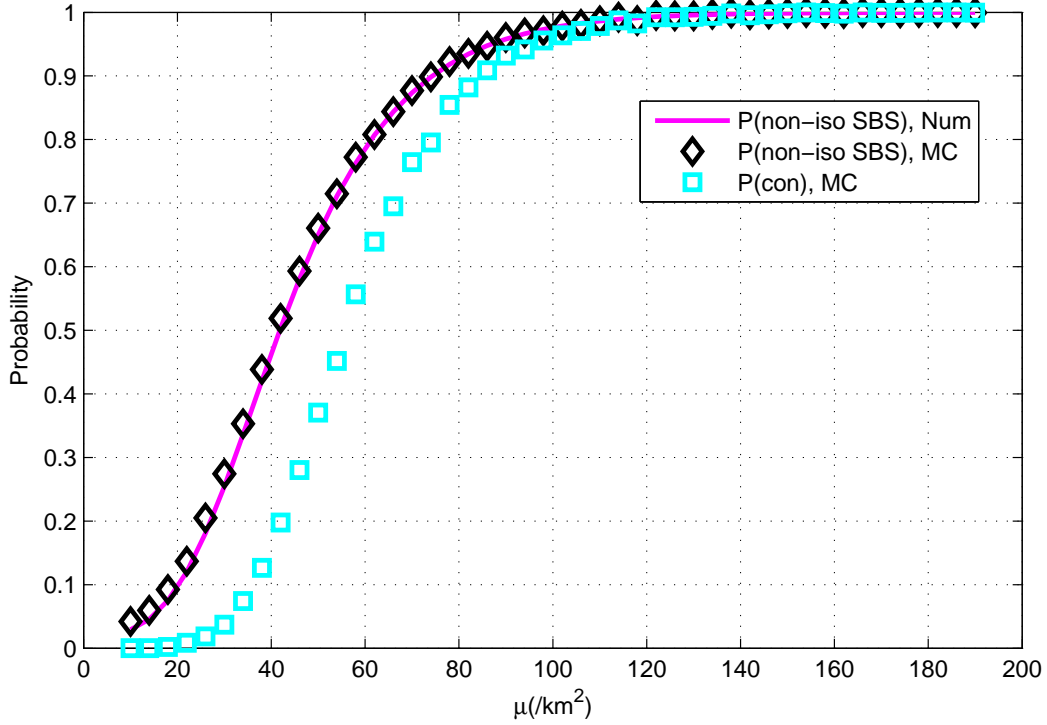


Fig. 4. $P(\text{non-iso SBS})$ and $P(\text{con})$

$P(\text{con}) \rightarrow 1$.

Proof: When the density of SBSs distribution is configured as μ , the distance between a SBS SBS_i , $1 \leq i \leq n$ and its closest SBS is D_i , the maximum value of the set of $\{D_i\}$ is denoted as D_0^{ni} , which is the minimum value for satisfying the constraint that there is no isolated SBS in the coverage of the MBS. When all SBSs in the coverage of the MBS are connected by a minimal spanning tree, the longest link in the minimal spanning tree is denoted as D_0^{con} , which is the minimal value for satisfying the constraint that all SBSs are connected in the coverage of the MBS.

Based on results in [29], when the density of SBSs in a square area is large enough, the value of D_0^{ni} will approach to the value of D_0^{con} , i.e., $\lim_{n \rightarrow \infty} P(D_0^{ni} = D_0^{con}) = 1$. When the density μ of SBSs in a circular area is large enough and the value of D_0 is fixed, we can derive a similarly result, i.e., $P(\text{non-iso SBS}) - P(\text{con}) \rightarrow 0$, $P(\text{non-iso SBS}) \rightarrow 1$ and $P(\text{con}) \rightarrow 1$. Based on the theorem 1, we can use the value of $P(\text{non-iso SBS})$ to replace the value of $P(\text{con})$ in

the following simulation analysis when the density of SBS in the coverage of the MBS is large enough, e.g., $100/(\pi R^2 \cdot km^2)$.

B. Network Capacity of Wireless Backhaul Networks

The optimization of wireless backhaul network can be achieved by the optimization of every connection cluster in the wireless backhaul network. Therefore, we propose the Theorem 2 to define the network capacity of a connection cluster in the wireless backhaul network.

Theorem 2: In the wireless backhaul network, the network capacity of a connection cluster consisting of M gateways and N SBSs satisfies:

$$C(M, N) \triangleq \min \left\{ \max_{\chi \in \Omega} \frac{\sum_{i=1}^N W_i}{Y^\chi(M, N)} + M \cdot W_S, M \cdot W_G \right\}. \quad (16)$$

where W_i , $1 \leq i \leq N$ is the transmission rate of wireless backhaul traffic at the SBS SBS_i and the value of W_i , $1 \leq i \leq N$, depends on the wireless channel capacity of different wireless links, $Y^\chi(M, N)$ is the average number of transmissions for transmitting a bit to a gateway, W_S is the transmission rate of backhaul traffic generated by a gateway, which is configured to be the same for every gateway, W_G is the gateway maximum transmission rate of backhaul traffic which includes the forwarding rate of wireless backhaul traffic generated from other SBSs and the transmission rate of backhaul traffic generated by a gateway.

Proof: Let $b_{i,j,k}$ be the k -th bit transmitted from the SBS SBS_i to its destination gateway GW_j , $h_{i,j,k}^\chi$ be the number of transmissions required to deliver $b_{i,j,k}$ to its destination gateway when the spatial and temporal scheduling algorithm $\chi \in \Omega$ is adopted. The average transmission number for transmitting a bit into a gateway is derived by

$$Y^\chi(M, N) = \lim_{T \rightarrow \infty} \frac{\sum_{i=1}^N \sum_{j=1}^M \sum_{k=1}^{N_{i,j,T}^\chi} h_{i,j,k}^\chi}{\sum_{i=1}^N \sum_{j=1}^M N_{i,j,T}^\chi}. \quad (17)$$

Considering the stability of wireless backhaul networks, the backhaul traffic at all SBSs are less than or equal to the backhaul traffic at all gateways. In this case, the backhaul traffic at all SBSs at a time slot is denoted by $\sum_{i=1}^N W_i$ in the wireless backhaul network. The average backhaul

traffic of a SBS is denoted by $\frac{\sum_{i=1}^N W_i}{N}$ in the wireless backhaul network. Let $t_{i,j,k,l}^x$, $1 \leq l \leq h_{i,j,k}^x$, be the time required to transmit $b_{i,j,k}$ in the l -th transmission in the wireless backhaul network and is derived by $t_{i,j,k,l}^x = \frac{N}{\sum_{i=1}^N W_i}$.

Remark 1. The total transmission time is first considered as the amount of traffic transmitted, measured in bits, multiplied by the time required to transmit each bit, in the wireless backhaul network on the individual SBS. Moreover, the total transmission time in the wireless backhaul network can also be calculated on the network level by evaluating the number of simultaneous transmissions in the entire wireless backhaul network. Obviously, the two values of total transmission time considering at SBSs and network level must be equal. On the basis of this observation, the Theorem 2 can be established.

At time T , the total transmission time T_{total} during $[0, T]$ includes the transmission time T_{gate} for backhaul traffic that has reached its gateway and the transmission time T_{norm} for backhaul traffic still in the transit at SBSs, i.e., $T_{total} = T_{gate} + T_{norm}$. Moreover, the transmission time T_{gate} is calculated by

$$\begin{aligned} T_{gate} &= \sum_{i=1}^N \sum_{j=1}^M \sum_{k=1}^{N_{i,j,T}^x} \sum_{l=1}^{h_{i,j,k}^x} t_{i,j,k,l}^x \\ &= \frac{N}{\sum_{i=1}^N W_i} \cdot \sum_{i=1}^N \sum_{j=1}^M \sum_{k=1}^{N_{i,j,T}^x} h_{i,j,k}^x. \end{aligned} \quad (18)$$

Let y_{\max}^x be the maximum number of hops in all routes of wireless backhaul network with the spatial and temporal scheduling algorithm χ , obviously $y_{\max}^x \leq N$. Since the wireless backhaul network is stable, there exists a small positive constant α , independent of T , such that the total amount of backhaul traffic in transit is bounded by αN . Hence

$$\begin{aligned} T_{norm} &\leq y_{\max}^x \alpha N t_{i,j,k,l}^x \\ &\leq \alpha N^2 t_{i,j,k,l}^x \\ &= \frac{\alpha N^3}{\sum_{i=1}^N W_i}. \end{aligned} \quad (19)$$

On the other hand, the total transmission time during $[0, T]$ calculated on the network level

equals $T_{total} = N \cdot T$. Therefore,

$$\frac{N}{\sum_{i=1}^N W_i} \cdot \sum_{i=1}^N \sum_{j=1}^M \sum_{k=1}^{N_{i,j,T}^X} h_{i,j,k}^X + T_{norm} = N \cdot T. \quad (20)$$

When the time interval of $[0, T]$ is sufficiently large and the wireless backhaul network is stable, the amount of traffic in transit is negligibly small compared with the amount of traffic that has already reached its gateway. Furthermore, we can obtain the following result:

$$\lim_{T \rightarrow \infty} \frac{\sum_{i=1}^N \sum_{j=1}^M \sum_{k=1}^{N_{i,j,T}^X} h_{i,j,k}^X}{\sum_{i=1}^N W_i \cdot T} = 1. \quad (21)$$

Based on (1) and (17), the transport capacity using the spatial and temporal scheduling algorithm χ in a connection cluster with M gateways and N SBSs is derived by

$$C^\chi(M, N) = \frac{\sum_{i=1}^N W_i}{Y^\chi(M, N)} + M \cdot W_S. \quad (22)$$

Based on (2), the network capacity of a connection cluster consisted of M gateways and N SBSs is derived by

$$C(M, N) \triangleq \max_{\chi \in \Omega} \frac{\sum_{i=1}^N W_i}{Y^\chi(M, N)} + M \cdot W_S. \quad (23)$$

Considering the maximum forwarding capacity of M gateways $M \cdot W_G$ and the stability of wireless backhaul networks, the network capacity of a connection cluster consisted of M gateways and N SBSs satisfies:

$$\min \left\{ \max_{\chi \in \Omega} \frac{\sum_{i=1}^N W_i}{Y^\chi(M, N)} + M \cdot W_S, M \cdot W_G \right\}. \quad (24)$$

C. Formulation and Decomposition of Cost Efficiency Optimization

With the massive MIMO and millimeter wave communication technologies adopting at 5G SBSs, SBSs have enough transmission rates used for wireless backhaul transmissions. However,

the cell size of SBSs is obviously reduced, e.g. the coverage radius of 50 meters. To guarantee the seamless coverage of 5G small cell networks, SBSs have to be deployed by an ultra-dense deployment solution. Hence, there exist a large number of SBSs in the 5G wireless backhaul network. Based on the Theorem 1, SBSs in a given coverage, e.g. the coverage of a macro cell, are formed into one connection cluster if the density of SBSs is larger than a specific threshold. Considering that SBSs are ultra-densely deployed in the 5G wireless backhaul network, all SBSs are assumed to be formed into one connection cluster in 5G wireless backhaul network. Based on the Theorem 2, the network capacity of wireless backhaul network increases with the increase of the number of gateways. However, the cost of wireless backhaul network is improved with the increasing of the number of gateways. Hence, it is a key issue for telecommunication providers to optimize the total cost efficient of 5G wireless backhaul networks.

Based on the result of Theorem 2, the cost efficiency of 5G wireless backhaul network with M gateways and N SBSs is defined as:

$$e(M, N) \triangleq \frac{C(M, N)}{\zeta (E_{EM} + E_{OP}) + M \cdot E_G}, \quad (25a)$$

$$E_{OP} = (P_{OP1} + P_{OP2}) \cdot T_{Lifetime}, \quad (25b)$$

$$P_{OP1} = M \cdot (a \cdot P_{Norm} \cdot W_G/W_0 + b), \quad (25c)$$

$$P_{OP2} = N \cdot (a \cdot P_{Norm} \cdot W_S/W_0 + b), \quad (25d)$$

where E_{EM} is the total embodied energy of wireless backhaul network which is fixed as the 20% of E_{EM} and E_{OP} [1], E_{OP} is the total operation energy of wireless backhaul network, which is calculated by the total operation energy consumed by gateways P_{OP1} and the total operation energy consumed by SBSs P_{OP2} in the lifetime of gateways and SBSs, P_{Norm} is the normalized transmission power associated with the normalized transmission rate W_0 at the gateway and SBS, a and b are fixed coefficients for computing the operation energy consumption [1], ζ is the conversion factor between the energy consumption and cost expense, E_G is the additional expense used for deploying the gateway.

Furthermore, the cost efficiency optimization of 5G wireless backhaul networks is formulated

as

$$\begin{aligned}
& \max_{M, W_i, \chi \in \Omega} e(M, N) \\
& s.t. \quad (1) W_i \leq c_l, \quad l \in \mathcal{L}_i^{out}, \forall SBS_i \in \mathcal{N} \\
& \quad (2) a_i^\tau + \sum_{SBS_p \in \mathcal{V}_i^{in}} r_{pi}^\tau = \sum_{SBS_q \in \mathcal{V}_i^{out}} r_{iq}^\tau, \quad \forall SBS_i \in \mathcal{N}, \quad SBS_i \neq d_\tau, \quad \forall \tau \in \mathcal{K} \\
& \quad (3) P_i \leq P_{\max}, \quad \forall SBS_i \in \mathcal{N}
\end{aligned} \tag{26}$$

where \mathcal{N} is the set of non-gateway SBSs (and \mathcal{M} , appearing in the next formula, is the set of gateway SBSs), P_{\max} is the maximum transmission power at the SBS.

To optimize the cost efficiency of wireless backhaul networks, the optimization of gateways and wireless backhaul routes need to be solved for wireless backhaul networks. In general, the optimization of gateways, including the configuration of the number and locations of gateways, can stay for a long time after the wireless backhaul network has been deployed. Hence, the optimization of gateways in wireless backhaul networks can be updated in a long time scale.

When the number and locations of gateways are fixed, the energy consumption of the backhaul network is changeless. Furthermore, the optimization of cost efficiency is simplified to the optimization of wireless backhaul network capacity, which benefits from the optimization of wireless backhaul routes. The optimization of wireless backhaul routes depends on the wireless channel capacity over every hop of wireless backhaul networks. Considering the time-varying characteristic of wireless channel capacity, the wireless backhaul routes in wireless backhaul networks have to be updated in a short time scale.

Based on the optimization requirements of wireless backhaul network in the long time and short time scales, a two-scale joint optimization solution is formulated as follows:

$$\max_{M, W_i, \chi \in \Omega} e(M, N) \begin{cases} \max_M e(M, N), \text{ in long time scale;} \\ \max_{W_i, \chi \in \Omega} C^x(M, N), \text{ in short time scale.} \end{cases} \tag{27a}$$

$$\begin{aligned}
& \max_M e(M, N) \\
& s.t. \quad \mathcal{M} \cup \mathcal{N} = \mathcal{V}, \mathcal{M} \cap \mathcal{N} = \phi.
\end{aligned} \tag{27b}$$

$$\begin{aligned}
& \max_{W_i, \chi \in \Omega} C^\chi(M, N) \\
& s.t. \ W_i \leq c_l, \ \forall l \in \mathcal{L} \\
& a_i^\tau + \sum_{SBS_p \in \mathcal{V}_i^{in}} r_{pi}^\tau = \sum_{SBS_q \in \mathcal{V}_i^{out}} r_{iq}^\tau, \ \forall SBS_i \in \mathcal{N}, \ SBS_i \neq d_\tau, \ \forall \tau \in \mathcal{K} \\
& P_i \leq P_{\max}, \ \forall SBS_i \in \mathcal{N}
\end{aligned} \tag{27c}$$

where \cup and \cap are operations of union and intersection on two sets, respectively.

Moreover, the channel status information (CSI) is important for optimizing the wireless backhaul routes in wireless backhaul networks. Without loss of generality, the following assumptions of CSI is declared in this study:

- 1) Every SB can obtain the local CSI which includes the CSI over every wireless channel associated with the local SBS;
- 2) The macro cell BS can obtain all CSI of wireless channels in the wireless backhaul network;

The spectrum efficiency over the link l is expressed by [15]

$$SE_l = \log_2 \left(\left| \mathbf{I}_{N_{S,T}^i} + \frac{P_i}{\sigma^2 N_{S,T}^i} \mathbf{F}_D^* \mathbf{F}_A^* \mathbf{H}_l \mathbf{P}_A \mathbf{P}_D \mathbf{P}_D^* \mathbf{P}_A^* \mathbf{H}_l^* \mathbf{F}_A \mathbf{F}_D \right| \right). \tag{28}$$

Moreover, the transmission capacity of the link l is derived by

$$c_l = B_s \cdot SE_l = B_s \cdot \log_2 \left(\left| \mathbf{I}_{N_{S,T}^i} + \frac{P_i}{\sigma^2 N_{S,T}^i} \mathbf{F}_D^* \mathbf{F}_A^* \mathbf{H}_l \mathbf{P}_A \mathbf{P}_D \mathbf{P}_D^* \mathbf{P}_A^* \mathbf{H}_l^* \mathbf{F}_A \mathbf{F}_D \right| \right). \tag{29}$$

where B_s is the bandwidth of link l . Based on the precoding/decoding optimization algorithms in [30], the maximum transmission capacity of the link l can be achieved. As a consequence, the optimization of wireless backhaul route can be achieved by maximizing the wireless transmission capacity of every link in wireless backhaul networks.

IV. OPTIMIZATION SOLUTION OF WIRELESS BACKHAUL NETWORKS

In this section, we give two algorithms to solve the optimization in two time scales, respectively.

A. Solution of Long time Scale Gateways Optimization

For a connection cluster with n SBSs, we propose a new algorithm to obtain the optimal number and location of gateways when the locations $\{(x_i, y_i), \ 1 \leq i \leq n\}$ of SBSs SBS_i are

known. To easily design the optimization algorithm in the long time scale, the transmission rate of wireless backhaul traffic at SBSs is configured as the maximum transmission rate W , i.e., $W_i = W$, $i \in \mathcal{N}$. The network capacity of a connection cluster is simplified as

$$C(M, N) \triangleq \max_{\chi \in \Omega} \frac{NW}{Y^\chi(M, N)} + M \cdot W_S. \quad (30)$$

To optimize the cost efficiency of wireless backhaul networks $e(M, N)$, the network capacity of a connection cluster needs to be maximized. To maximize the network capacity of a connection cluster, the number of hops in wireless traffic route must be minimized. This optimization is different from the convex optimization. In general, a convex optimization problem can be solved by many iterations of the algorithms and the iterations won't stop until the result converges to the optimal solution. But this optimization problem can be solved by traversal algorithms instead of iterative algorithms. However, a complete traversal will cost much time for a large number of iterations. Algorithm 2 proposed here is a more efficient traversal algorithm which obtains a suboptimal solution with lower complexity instead of the global optimal solution. Algorithm 2 is developed as follows.

The complexity of Algorithm 2 is analyzed in the following. For the function of *KnowGateway()* in the Algorithm 2, the worst result occurs when there is only one SBS in the range of one hop. In this case, the complexity of function *KnowGateway()* is $O(n^3)$. Moreover, the function *KnowGateway()* is called by the function *UnknowGateway()* with $O(n)$ times. Furthermore, the total complexity of Algorithm 2 is $O(n^4)$.

B. Solution of Short Time Scale Routes Optimization

After the number and locations of gateways are optimized in the long time scale, wireless backhaul routes of wireless backhaul networks can be optimized in the short time scale. Based on system model in Fig. 1, all SBSs report the local CSI to the macro cell BS in a time slot. The macro cell BS works out the optimal backhaul route information and then sends the optimal backhaul route information to all SBSs in the next time slot, as depicted in Fig. 5.

Based on the CSI reported by N SBSs, a directional connected graph with weight $G = (\mathcal{V}, \mathcal{L})$ is formed for the wireless backhaul network with M gateways, where \mathcal{V} is the set of SBSs and \mathcal{L} is the link set of wireless backhaul routes. A SBS can have multiple input links but only one output link in the weighted directional connected graph, where the weights of directed links

Algorithm 2 Long Time Optimization Solution. (Part I)

Input: MAX_M , n , the location of all the small cell BSs $\{(x_p, y_p), SBS_p \in \mathcal{V}\}$

Output: M_{opt} , \mathbf{PS}_M .

for $M = 1 : MAX_M$ **do**

The minimum average hop number of wireless backhaul traffic in the M gateways macro cell is:

$$\min_{\chi \in \Omega} Y^\chi(M, N) \leftarrow \text{UnknowGateway}(\{(x_p, y_p), SBS_p \in \mathcal{V}\}, M);$$

The position of M gateways are:

$$\mathbf{PS}_M = \{(x_q, y_q), SBS_q \in \Phi_G\};$$

end for

Choose M making energy efficiency to be the biggest:

$$M_{opt} \leftarrow \arg \max_M e(M, N);$$

function UnknowGateway ($\{(x_p, y_p), SBS_p \in \mathcal{V}\}, M$)

1) **Initialization:** Put all the small cell BSs into the set of small cell BS Φ_S and empty the set of gateway Φ_G .

2) **while** $|\Phi_G| < M$ **do**

$Array = \text{zeros}$

for $SBS_i : SBS_i \in \Phi_S$ **do**

Put small cell BS SBS_i into set Φ_G :

$$\Phi_G = \Phi_G + \{SBS_i\};$$

Call function KnowGateway, then save the result returned by KnowGateway into an array $Array$:

$$Array_i \leftarrow \text{KnowGateway}(\{(x_p, y_p), SBS_p \in \mathcal{V}\}, |\Phi_G|, \{(x_q, y_q), SBS_q \in \Phi_G\});$$

Remove the small cell BS SBS_i out of set Φ_G :

$$\Phi_G = \Phi_G - \{SBS_i\};$$

end for

Put the small cell BS SBS_i making $Array_i$ to be the biggest into set Φ_G , and remove it from the set of small cell BS Φ_S :

$$k \leftarrow \arg \min_i Array_i$$

$$\Phi_G = \Phi_G + \{SBS_k\}; \Phi_S = \Phi_S - \{SBS_k\};$$

end while

3) **if** $M > 1$ **then**

for $SBS_j : SBS_j \in \Phi_G$ **do**

$Array = \text{zeros}, Array_j \leftarrow \text{KnowGateway}(\{(x_p, y_p), SBS_p \in \mathcal{V}\}, |\Phi_G|, \{(x_q, y_q), SBS_q \in \Phi_G\});$

for $SBS_i : SBS_i \in \Phi_S$ **do**

Exchange SBS_j with SBS_i (Put SBS_j into the set of small cell, and remove it out of the set of gateway; Put SBS_i into the set of gateway, and remove it out of the set of small cell), then

$$Array_i \leftarrow \text{KnowGateway}(\{(x_p, y_p), SBS_p \in \mathcal{V}\}, |\Phi_G|, \{(x_q, y_q), SBS_q \in \Phi_G\});$$

Exchange back SBS_j with SBS_i ;

end for

$$k \leftarrow \arg \min_i Array_i$$

$$\Phi_G = \Phi_G + \{SBS_k\}; \Phi_S = \Phi_S - \{SBS_k\};$$

if $k \neq j$ **then**

Exchange SBS_j with SBS_k ;

end if

end for

end if

end function

Algorithm 2 Long Time Optimization Solution. (Part II)

function KnowGateway($\{(x_p, y_p), SBS_p \in \mathcal{V}\}, M, \{(x_q, y_q), GW_q \in \mathcal{M}\}$)

1) **Initialization:** For all the small cell BSs, $state(i) = 0, SBS_i \in \mathcal{V} - \mathcal{M}$; All the gateways are 0 hop BSs.

2) **for** $GW_j : GW_j \in \mathcal{M}$ **do**

 Empty all the sets Φ_h , variable $h \leftarrow 0$; Put gateway GW_j into Φ_0 :

$$\Phi_h = \Phi_h + \{GW_j\};$$

while Φ_h **do**

for $SBS_k \in \Phi_h$ **do**

for $SBS_i \in \mathcal{V} - \mathcal{M}$ **do**

 The distance between small cell BS SBS_i and SBS_k is D_{ik} :

$$D_{ik} \leftarrow \sqrt{(x_i - x_k)^2 + (y_i - y_k)^2};$$

if $state(i) == 0 \&\& D_{ik} \leq D_0$ **then**

 The minimum hop number between small cell BS SBS_i and gateway GW_j is $h + 1$, then put small cell BS SBS_i into set Φ_{h+1} and change the state of small cell BS SBS_i $state(i)$ into 1:

$$hop(i, j) \leftarrow h + 1; \Phi_{h+1} = \Phi_{h+1} + \{SBS_i\};$$

end if

end for

end for

 Search the small cell BSs whose minimum hop number backhauling to gateway GW_j is $h + 1$:

$$h \leftarrow h + 1;$$

end while

end for

3) The routing link with minimum hop number is selected for relaying the wireless backhaul traffic between the small cell BS SBS_i and the corresponding gateway:

$$hop(i) \leftarrow \min_{GW_j \in \mathcal{M}} hop(i, j);$$

4) The minimum average hop number of wireless backhaul traffic in the macro cell is calculated by:

$$\min_{\chi \in \Omega} Y^\chi(M, N) \leftarrow \frac{\sum_{SBS_i \in \mathcal{V} - \mathcal{M}} hop(i)}{|\mathcal{V} - \mathcal{M}|};$$

5) **return** $\min_{\chi \in \Omega} Y^\chi(M, N)$.

end function

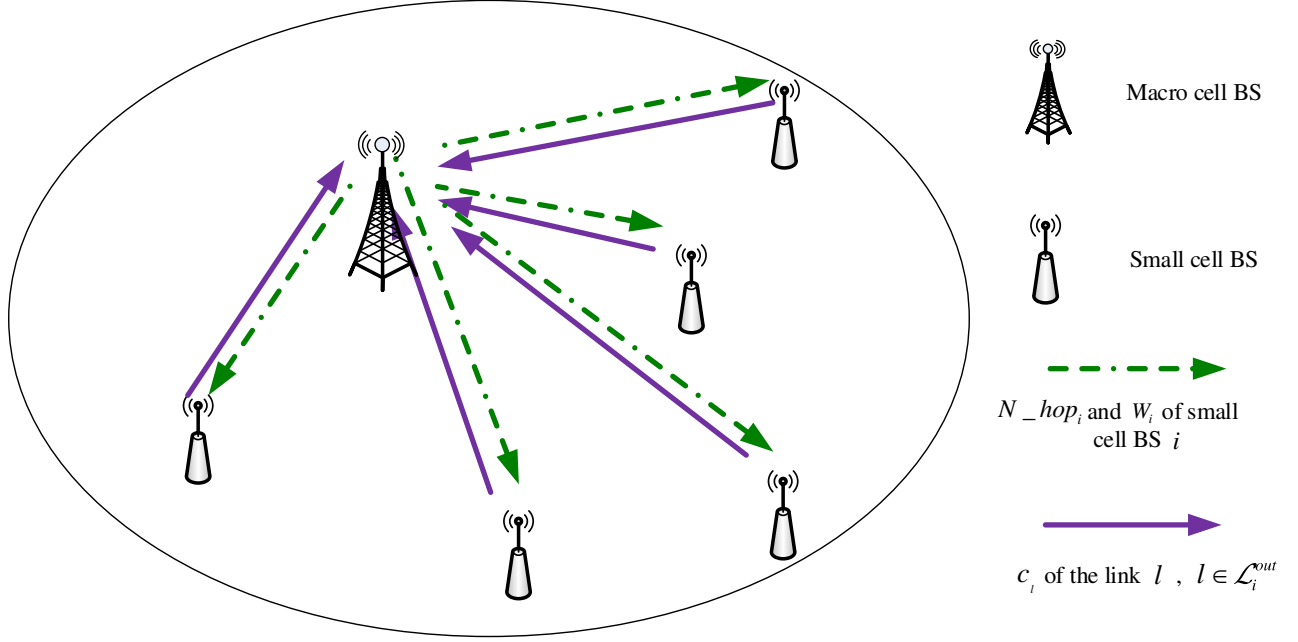


Fig. 5. Wireless backhaul route schedule process

correspond to the traffic rates. In the end, the wireless backhaul route has a tree topology with the root node at a gateway. If there are multiple gateways in the wireless backhaul network, the wireless backhaul routes are represented by multiple tree topologies in the wireless backhaul network, i.e., every tree topology has a root node at a gateway. In this case, the short time scale optimization solution is obtained by first translating the weighted directed connected graph into multiple tree topologies. Moreover, the generated tree topology can maximize the network capacity of a connection cluster and satisfy three constraints: a) the root node of the tree topology is a gateway; b) the transmission rate of SBS wireless backhaul traffic, which corresponds to the weight of corresponding directed link, is less than or equal to the wireless channel capacity; c) the wireless backhaul traffic need to be balanced at SBSs. Furthermore, the average transmission number is calculated by

$$Y^x(M, N) = \frac{\sum_{i=1}^N hop_i}{N}, \quad (31)$$

where hop_i is the hop number between the SBS SBS_i and the gateway. Thus, the network

capacity of wireless backhaul network is calculated by

$$C(M, N) \triangleq \max_{\chi \in \Omega} \frac{N \cdot \sum_{i=1}^N W_i}{\sum_{i=1}^N \text{hop}_i}. \quad (32)$$

Based on three constrains and (33), a maximum capacity spanning tree (MCST) algorithm is developed to obtain the tree topology with maximum network capacity $T = (\mathcal{U}, \mathcal{TL})$, where \mathcal{U} is the set of nodes, \mathcal{TL} is the link set. The detail MCST algorithm is illustrated in Algorithm 3.

Algorithm 3 MCST Algorithm.

Input: The set of gateways \mathcal{M} and the set of SBSs \mathcal{N} , wireless channel capacities over all wireless links in the wireless backhaul network.

- 1) **Initialization:** The set of node $\mathcal{U} = \mathcal{M}$, the set of candidate links \mathcal{CL} including all links between nodes $Z_j \in \mathcal{M}, 1 \leq j \leq M$ and $Z_i \in \mathcal{N}, 1 \leq j \leq N$, the hop number between the gateway and the node $Z_j \in \mathcal{M}$ is 0, empty the set of link \mathcal{TL} .

- 2) **while** $\mathcal{V} - \mathcal{U}$ **do**

Traverse the link in the set of candidate links $((Z_j, Z_v), Z_j \in \mathcal{U}, Z_v \in \mathcal{V} - \mathcal{U})$, then

choose the link making $\frac{(|\mathcal{U} - \mathcal{M}| + 1) \cdot \left(\sum_{Z_i \in \mathcal{U} - \mathcal{M}} W_i + W_{v, \text{tmp}} \right)}{\sum_{Z_i \in \mathcal{U} - \mathcal{M}} \text{hop}_i + \text{hop}_{v, \text{tmp}}}$ to be the biggest capacity (where

$\text{hop}_{v, \text{tmp}} \leftarrow \text{hop}_j + 1$ is the number of hop between the gateway and a temporary node $Z_{v, \text{tmp}} \in \mathcal{V} - \mathcal{U}$, W_i and $W_{v, \text{tmp}}$ are restricted by the constrains of b) and c)), then

Put (Z_j, Z_v) into the set of links \mathcal{TL} ; Put Z_v into \mathcal{U} :

$$\mathcal{U} = \mathcal{U} + \{Z_v\};$$

The number of hop hop_v between the gateway and the node Z_v is one more than the number hop_j of hop between the gateway and the node Z_j :

$$\text{hop}_v \leftarrow \text{hop}_j + 1;$$

The next hop node N_hop_v between the gateway and the node Z_v is assigned by Z_j :

$$N_hop_v = Z_j;$$

Update the candidate links in \mathcal{CL} : The set of candidate links \mathcal{CL} only includes all links between nodes $Z_j \in \mathcal{U}$ and $Z_v \in \mathcal{V} - \mathcal{U}$

end while

Output: \mathcal{TL}, N_hop .

TABLE I
DEFAULT PARAMETERS OF SIMULATION SYSTEMS

Parameters	Default values
The maximum distance of every hop D_0	200 meters [31]
The radius of macro cell R	500 meters
The density of SBSs in a wireless backhaul network μ	$100/(\pi R^2 \cdot km^2)$
The conversion factor ζ	1 €/kWh [32]
Lifetime of SBS $T_{Lifetime}$	5 years [33]
The fixed coefficient a	7.84
The fixed coefficient b	71.5 Watt
The normalized transmission power at SBS P_{Norm}	1 Watt
The normalized transmission rate at SBS W_0	1 Gbps
The additional expense used for deploying the gateway E	3900€ [34]
Wave length of millimeter wave λ	5 millimeters
Path loss coefficient γ	2 [35]
Distance among antennas d	2.5 millimeters
Number of transmission antennas at SBS N_T	16
Number of receive antennas at SBS N_R	128
Number of RF chains at a transmitter N_{RF}^T	4
Number of RF chains at a receiver N_{RF}^R	4
Number of data stream $N_{S,T}^i$	2
The maximum transmission power P_{max}	1 Watt
The maximum forwarding capacity of the gateway W_G	100 Gbps
Bandwidth of SBSs B_s	1 GHz

V. SIMULATION RESULTS AND DISCUSSION

Based on the proposed two-scale joint optimization algorithm, the effect of various system parameters on the cost efficiency and network capacity is analyzed and compared by numerical simulations in this section. Without loss of generality, the number of data streams $N_{S,T}^i$ at every SBS is configured to be the same. The maximum transmission rate of wireless backhaul traffic at every SBS is configured as $W = 10\text{Gbps}$ considering the millimeter wave technology. The detailed parameters of simulation system are illustrated in Table I.

Fig. 6 illustrates the cost efficiency of 5G wireless backhaul networks with respect to the density of total SBSs with different number of gateways. When the number of gateways is fixed, the cost efficiency of 5G wireless backhaul networks increases with the increase of the density of SBSs. When the total SBSs is fixed, there exists a maximum cost efficiency in 5G wireless backhaul networks with different number of gateways. Moreover, the number of

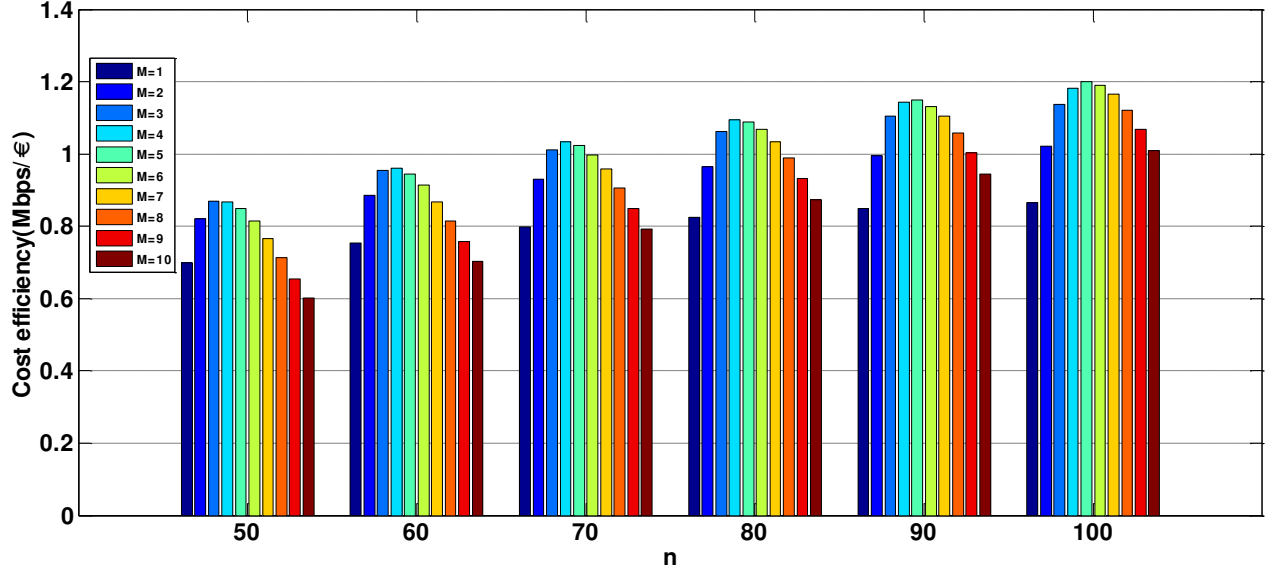


Fig. 6. Cost efficiency of 5G wireless backhaul networks with respect to total SBSs with different number of gateways.

gateways corresponding to the maximum cost efficiency increases with the increase of the total SBSs in 5G wireless backhaul networks.

Fig. 7 shows the network capacity of 5G wireless backhaul networks with respect to the SNR over wireless channels and different number of gateways. When the number of gateways is fixed, the network capacity of 5G wireless backhaul networks increases with the increase of SNR values over wireless channels. When the SNR value is fixed, the network capacity of 5G wireless backhaul networks increases with the increase of number of gateways.

Fig. 8 describes the cost efficiency of 5G wireless backhaul networks with respect to the SNR over wireless channels and different number of gateways. When the number of gateways is fixed, the cost efficiency of 5G wireless backhaul networks increases with the increase of the SNR values over wireless channels. When the SNR value is fixed over wireless channels, there exists a maximum cost efficiency in 5G wireless backhaul networks with different number of gateways. Moreover, the optimal number of gateways corresponding to the maximum cost efficiency is 5.

When the optimal number and positions of gateways are fixed in 5G wireless backhaul networks, we compare the proposed MCST algorithm with the typical shortest path (SP) algorithm [36], [37] in Fig. 9. Fig. 9 shows the cost efficiency of 5G wireless backhaul networks with respect

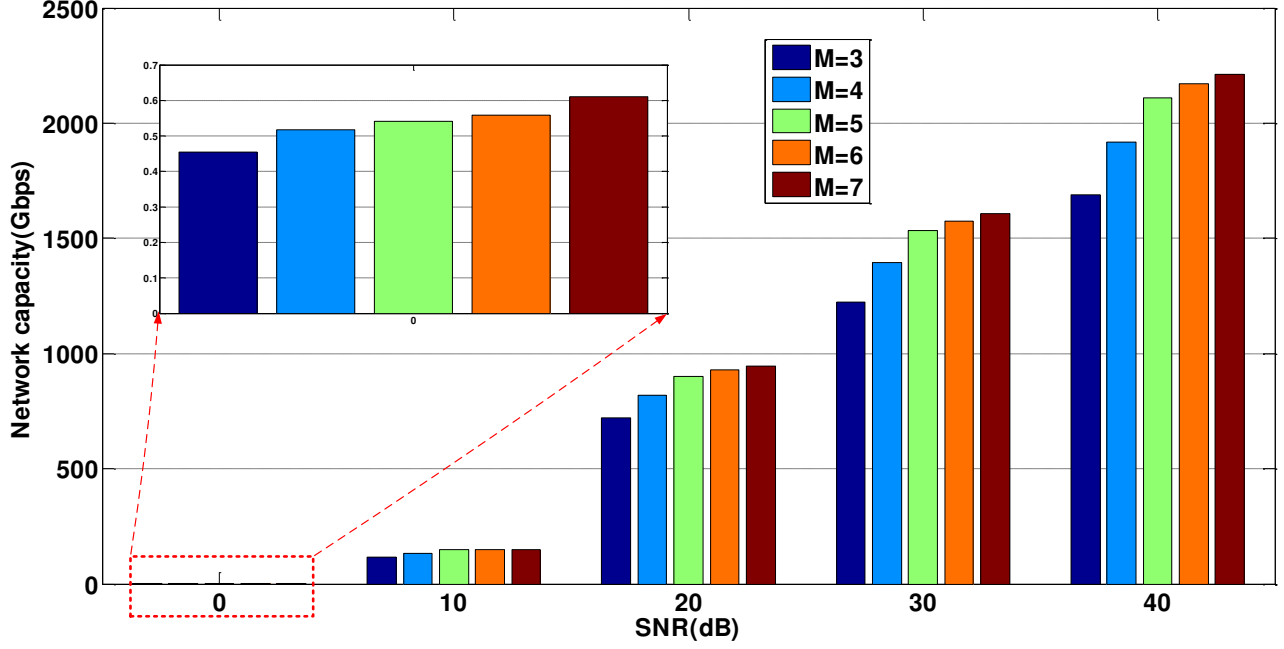


Fig. 7. Network capacity of 5G wireless backhaul networks with respect to the SNR over wireless channels and different number of gateways.

to the MCST algorithm and SP algorithm considering different SNR values. From Fig. 9(a), the cost efficiency of MCST algorithm is always larger than that of SP algorithms in 5G wireless backhaul networks. Based on results in Fig. 9(b), the maximum improvement of cost efficiency is 381% for the MCST algorithm when the number of gateway is one. When the number of gateway is five, the maximum improvement of network capacity is 13% for the MCST algorithm based on results in Fig. 9(b).

VI. CONCLUSIONS

In this paper, a two-scale cost efficiency optimization algorithm is proposed for 5G wireless backhaul networks. In the long time scale, the number and positions of gateways are optimized by the LTO algorithm. In the short time scale, the network capacity is optimized by the MCST algorithm. Numerical results show that there exists an optimal number of gateways for the maximum cost efficiency of 5G wireless backhaul networks and the MCST algorithm can significantly improve the cost efficiency of 5G wireless backhaul networks. Our results provide useful guideline for the deployment and optimization of 5G wireless backhaul networks.

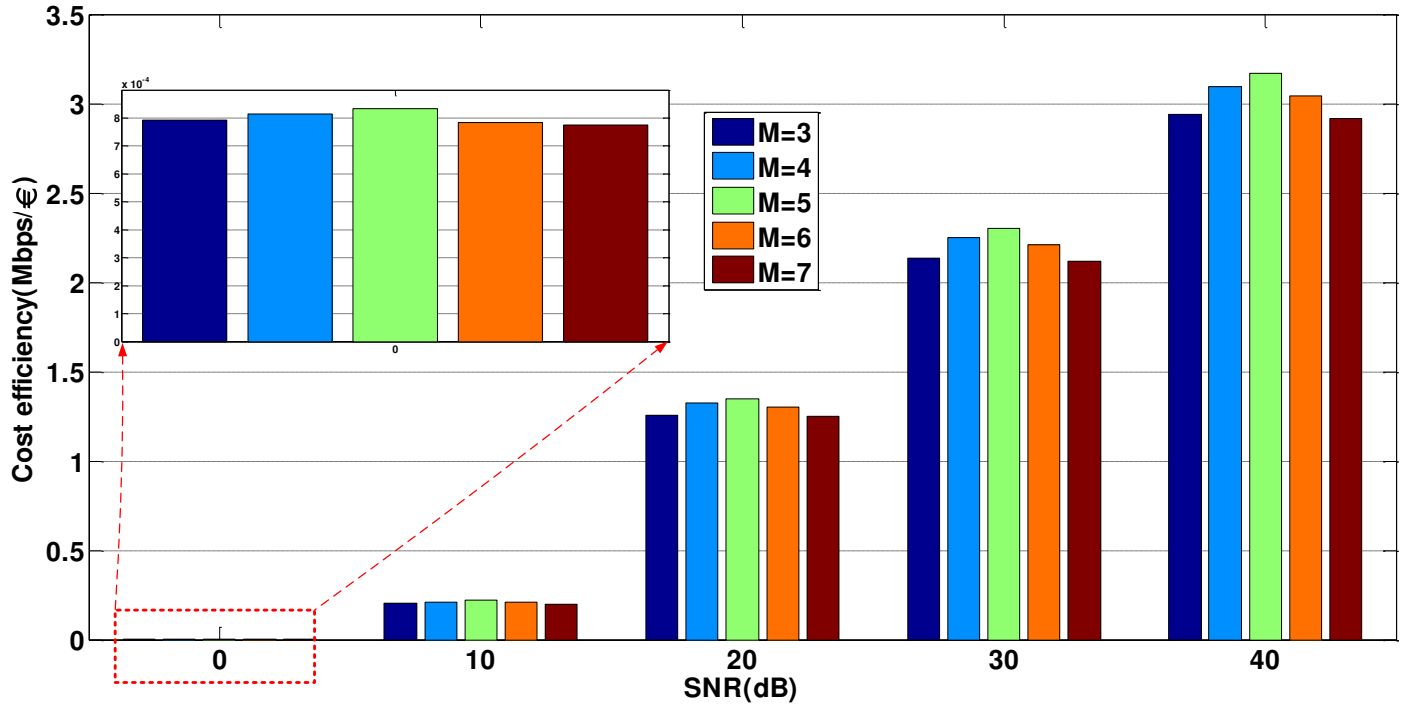


Fig. 8. Cost efficiency of 5G wireless backhaul networks with respect to the SNR over wireless channels and different number of gateways.

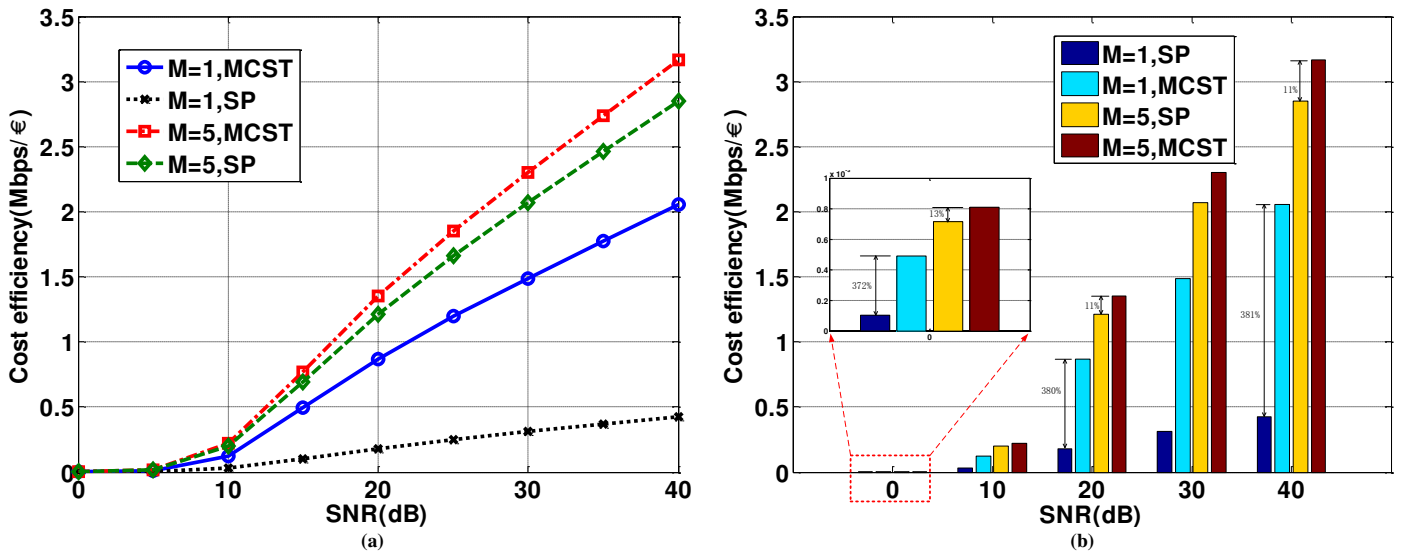


Fig. 9. Cost efficiency of 5G wireless backhaul networks with respect to the SNR over wireless channels and different number of gateways.

REFERENCES

- [1] I. Humar, X. Ge, L. Xiang, J. Ho, and M. Chen, "Rethinking energy-efficiency models of cellular networks with embodied energy," *IEEE Network*, vol.25, no.3, pp.40–49, Mar. 2011.
- [2] N. Bhushan, J. Li, D. Malladi and R. Gilmore, "Network densification: the dominant theme for wireless evolution into 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 82–89, Feb. 2014.
- [3] X. Ge, S. Tu, G. Mao, C.-X. Wang and T. Han, "5G Ultra-Dense Cellular Networks," *IEEE Wireless Commun.*, vol. 23, no. 1, pp.72–79, Feb. 2016.
- [4] X. Ge, H. Cheng, M. Guizani and T. Han, "5G wireless backhaul networks: challenges and research advances," *IEEE Network*, vol. 28, no. 6, pp. 6–11, Nov. 2014.
- [5] Z. Gao, L. Dai, D. Mi, Z. Wang, M. A. Imran and M. Z. Shakir, "MmWave massive-MIMO-based wireless backhaul for the 5G ultra-dense network," *IEEE Wireless Commun.*, vol. 22, no. 5, pp.13–21, Oct. 2015.
- [6] Z. Zhang, X. Wang, K. Long, A. V. Vasilakos and L. Hanzo, "Large-scale MIMO-based wireless backhaul in 5G networks," *IEEE Wireless Commun.*, vol. 22, no. 5, pp.58–66, Oct. 2015.
- [7] S. Hur, T. Kim, D. J. Love, J. V. Krogmeier, T. A. Thomas and A. Ghosh, "Millimeter wave beamforming for wireless backhaul and access in small cell networks," *IEEE Trans. Commun.*, vol. 61, no. 10, pp. 4391–4403, Oct. 2013.
- [8] P. T. Dat, A. Kanno, K. Inagaki and T. Kawanishi, "High-capacity wireless backhaul network using seamless convergence of radio-over-fiber and 90-GHz millimeter-wave," *J. Lightwave Technol.*, vol. 32, no. 20, pp. 3910–3923, Oct. 2014.
- [9] R. Taori and A. Sridharan, "Point-to-multipoint in-band mmwave backhaul for 5G networks," *IEEE Commun. Mag.*, vol. 53, no. 1, pp. 195–201, Jan. 2015.
- [10] L. Wei, R. Hu, Y. Qian, and G. Wu, "Key elements to enable millimeter wave communications for 5G wireless systems," *IEEE Wireless Commun.*, vol. 21, no. 6, pp. 136–143, Jan. 2015.
- [11] K. Zheng, L. Zhao, J. Mei, M. Dohler, W. Xiang, and Y. Peng, "10 Gb/s Hetsnets with millimeter-wave communications: Access and networking," "Challenges and protocols," *IEEE Commun.*, vol. 53, no. 1, pp. 222–231, Jan. 2015.
- [12] X. Ta, G. Mao and B. D. Anderson, "On the giant component of wireless multihop networks in the presence of shadowing," *IEEE Trans. Veh. Technol.*, vol. 58, no. 9, pp. 5152–5163, Jun. 2009.
- [13] A. A. Kannan, B. Fidan, and G. Mao, "Robust distributed sensor network localization based on analysis of flip ambiguities," in *Proc. IEEE Globecom 2008*, pp. 1–6, Dec. 2008.
- [14] G. Mao, and B. D. Anderson, "Graph theoretic models and tools for the analysis of dynamic wireless multihop networks," in *Proc. IEEE WCNC*, pp. 1–6, May 2009.
- [15] A. Mesodiakaki, F. Adelantado, L. Alonso, M. Di Renzo and C. Verikoukis, "Energy and spectrum efficient user association in millimeter wave backhaul small cell networks," *IEEE Trans. Veh. Technol.*, vol. PP, no. 99, pp. 1–1, May. 2016.
- [16] E. Pateromichelakis, M. Shariat, A. Ul Quddus and R. Tafazolli, "Joint routing and scheduling in dense small cell networks using 60 GHz backhaul," in *Proc. IEEE ICCW 2015*, pp. 2732–2737, Jun. 2015.
- [17] M. P. Anastasopoulos, P. D. M. Arapoglou, R. Kannan and P. G. Cottis, "Adaptive routing strategies in IEEE 802.16 multi-hop wireless backhaul networks based On evolutionary game theory," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 7, pp. 1218–1225, Sep. 2008.
- [18] H. Miao and M. Faerber, "Self-organized multi-hop millimeter-wave backhaul network: Beam alignment and dynamic routing," in *Proc. IEEE EuCNC 2015*, Paris, pp. 275–279, 2015.
- [19] W. Ni, I. B. Collings, X. Wang and R. P. Liu, "Multi-hop point-to-point FDD wireless backhaul for mobile small cells," *IEEE Wireless Commun.*, vol. 21, no. 4, pp. 88–96, Aug. 2014.

- [20] X. Ge, S. Tu, T. Han, Q. Li, G. Mao, "Energy efficiency of small cell backhaul networks based on Gauss-Markov mobile models," *IET Networks*, vol. 4, no. 2, pp. 158–167, Mar. 2015.
- [21] X. Ge, L. Pan, S. Tu, H. Chen and C. Wang, "Wireless Backhaul Capacity of 5G Ultra-Dense Cellular Networks," in *Proc. IEEE VTC-Fall*, Montreal, Sep. 2016.
- [22] G. Mao, Z. Lin, X. Ge and Y. Yang, "Towards a simple relationship to estimate the capacity of static and mobile wireless networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 8, pp. 3883–3895, Aug. 2013.
- [23] S. Singh, M. N. Kulkarni, A. Ghosh and J. G. Andrews, "Tractable model for rate in self-backhauled millimeter wave cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 10, pp. 2196–2211, Oct. 2015.
- [24] A. Liu, V. K. N. Lau, F. Zhuang and J. Chen, "Two timescale joint beamforming and routing for multi-antenna D2D networks via stochastic cutting plane," *IEEE Signal Process.*, vol. 63, no. 18, pp. 4854–4865, Sep. 2015.
- [25] M. N. Kulkarni, A. Ghosh and J. G. Andrews, "A comparison of MIMO techniques in downlink millimeter wave cellular networks with hybrid beamforming," *IEEE Trans. Commun.*, vol. 64, no. 5, pp. 1952–1967, May 2016.
- [26] R. L. Graham, B. D. Lubachevsky, K. J. Nurmela and P. R. J. Östergård, "Dense packings of congruent circles in a circle," *Discrete Mathematics*, vol. 181, pp. 139–154, 1998.
- [27] W. Huang and T. Ye, "Global optimization method for finding dense packings of equal circles in a circle," *Eur. J. Oper. Res.*, vol. 210, no. 3, pp. 474–481, 2011.
- [28] C. Bettstetter, "On the connectivity of ad hoc networks," *Computer Journal*, vol. 47, no. 4, pp. 432–447, 2011.
- [29] M. D. Penrose, "The longest edge of the random minimal spanning tree," *Annals of Applied Probability*, vol. 7, no. 2, pp. 340–361, 1997.
- [30] O. E. Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi and R. W. Heath, "Spatially sparse precoding in millimeter wave MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 1499–1513, Mar. 2014.
- [31] S. Sun, T. S. Rappaport, R. W. Heath, A. Nix and S. Rangan, "Mimo for millimeter-wave wireless communications: beamforming, spatial multiplexing, or both?" *IEEE Commun. Mag.*, vol. 52, no. 12, pp. 110–121, Dec. 2014.
- [32] B. Lee and S. Kim, "Characterizing energy and deployment efficiency relations in cellular systems," in *Proc. IEEE ICSPCS 2012*, Gold Coast, QLD, pp. 1–5, Dec. 2012.
- [33] C. Khirallah, J. S. Thompson, and H. Rashvand, "Energy and cost impacts of relay and femtocell deployments in long-term-evolution advanced," *IET Commun.*, vol. 5, no. 18, pp. 2617–2628, Jul. 2011.
- [34] K. Johansson, "Cost effective deployment strategies for heterogeneous wireless networks," Ph.D. dissertation, KTH Info. and Commun. Tech., Stockholm, Sweden, Nov. 2007.
- [35] A. Ghosh, T. A. Thomas, M. C. Cudak, R. Ratasuk, P. Moorut, F. W. Vook, T. S. Rappaport, G. MacCartney, S. Sun, and S. Nie, "Millimeter wave enhanced local area systems: A high data rate approach for future wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1152–1163, Jun. 2014.
- [36] I. Banerjee, I. Roy, A. R. Choudhury, B. D. Sharma and T. Samanta, "Shortest path based geographical routing algorithm in wireless sensor network," in *In Proc. IEEE CODIS 2012*, Kolkata, pp. 262–265, Dec. 2012.
- [37] R. C. Prim, "Shortest connection networks and some generalizations," *The Bell System Technical Journal*, vol. 36, no. 6, pp. 1389–1401, Nov. 1957.